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THE DYNAMICS OF LONGITUDINAL (FIELD-ALIGNED) CURRENTS IN THE MAGNETOSPHERE

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An old hypothesis by Birkeland [1] regarding longitudinal currents along the geomagnetic lines of force has recently drawn increasing attention by investigators. In the context of contemporary theory and experiment, the attraction of this hypothesis is that it opens up a tempting possibility of explaining a whole series of geophysical phenomena [2] (VLF measured in the polar ionosphere, precipitation of energetic (up to 40 Kev) particles during polar auroral, etc.) not susceptible of explanation solely on the basis of ionospheric currents. /1*

The difficulty in studying the longitudinal (field-aligned) currents in the Earth's magnetosphere stems primarily from the fact that these currents must excite turbulence, and the problem of the turbulent, electrically-conducting plasma is far from being completely resolved at present. However, as turbulent plasma physics develops with the introduction of new theoretical and experimental data, the problem of the field-aligned currents is beginning to become clearer.

It is important to note at the outset that geophysical data pertaining to currents in the magnetosphere can aid in the solution of the general problems of turbulent electroconductivity in plasma.

The fact is that turbulent plasma in space is formed under such conditions that it is not susceptible to laboratory simulation. We are not able to explain in the laboratory how the currents will flow in a collision-free, unbounded, low-density plasma in a constant electric field over a sufficiently long interval of time, under quasi-stationary conditions. /2

References 3-9 deal with theoretical investigations of the problem, essentially only the initial stage of the process of growth of turbulence in a constant external electric field, when the escape of resonance ions and electrons is yet insignificant. In addition, there are discrepancies between these theoretical works stemming from the many assumptions and suppositions.

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*Numbers in the margin indicate pagination in the foreign text.

One possible approach to solving this problem might be: Assuming that in the quasi-stationary state the role of escaping particles will be somehow limited for a sufficiently long existence of the turbulence, we extrapolate the generalized Ohm's law for the turbulent state, as given by theory and experiment for the onset of the quasi-stationary turbulence, over a sufficiently long time [9].

Having made this assumption and drawn inferences from it, an attempt can be made to compare them with the data from geophysical observations and experiments. This is the approach we shall adopt in this paper.

In reference [10] Swift proposed that the region of the magnetosphere near the auroral zone be thought of as a ion-sound turbulence region. Reference [10] was based on the experimental facts that the electrons precipitating during auroral acquire their energy immediately at the time of precipitation, that there are ionosphere currents of up to 10^5 amperes during polar auroral whose closure is unknown, and on the presence of high levels of VLF in the auroral zone during auroral phenomena, from both ground-based- and satellite-data. These experimental facts are explained if it is assumed that charge separation can develop in the Earth's magnetosphere, creating currents along the magnetic field lines and through the conducting ionosphere, uniting space-charge regions. If the current intensity in the plasma is high enough, turbulence is generated, leading to "collective collisions" between particles and waves, and, consequently, to an anomalous resistance of the magnetosphere plasma. As a result of the generation of the anomalous resistance, substantial potential differences can be produced along the lines of force, resulting in the turbulent heating of electrons up to Kev-energies. We emphasize that from a contemporary viewpoint reference [11] is only qualitatively correct, and does not provide a quantitative picture of the described process. The question of anomalous resistance in the Earth's magnetosphere has also been treated in [11], where it was underscored that the usual theoretical findings relating to anomalous resistance in a non-isothermal plasma [3, 4] in the presence of a magnetic field are completely valid only if it is small enough, since $\omega_{he} \ll \omega_{pe}$, i.e.

/3

$$H \ll \sqrt{n}\left(\sqrt{4\pi m_e c^2}\right) = 3\cdot 10^{-3}\sqrt{n_e} \text{ (oersted)}.$$

Further, in the case of very large fields (not realized in the magnetosphere) the quasi-linear current limitation completely disappears.

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Since beyond the plasma-pause in the magnetosphere the density is observed to

be quite low, according to Carpenter's data $r \sim 1$ cm^{-3} (illegible in text) (see, for example [12]), the phenomenon of anomalous resistance for these regions cannot be described quantitatively within the context of the quasi-linear theory [3, 4], since the condition $\omega_{he} << \omega_{pe}$ is not satisfied (in the plasma-pause, in the equatorial plane, $\omega He \sim \omega pe$).

In reference [11] doubt is expressed as to the existence of the anomalous resistance with current flow in low-density regions, although this question has not been given rigorous treatment by anyone, either theoretically or experimentally.

With densities of $r \sim 100$ cm^{-3} the quasi-linear theory describing anomalous resistance in the magnetosphere is apparently well enough grounded to be used.

On the other hand, reference [13] comfirms experimentally the presence of turbulence and anomalous resistance in the magnetosphere with the flow of large longitudinal (field-aligned) currents. In this paper the damping of the Pe-4 and Pi-2 oscillations, with $T \sim 40$-100 sec (corresponding to MHD-waves in the magnetosphere), is established. We present in this paper a diagram from this reference (Fig. 1). As can be seen from the diagram, the decrement is quite small with low bay amplitudes and does not depend on the bay amplitude. Then, beginning with bay amplitudes of 12γ-100γ, the decrement increases. After this the decrement does not change with an increase in bay amplitude δH.

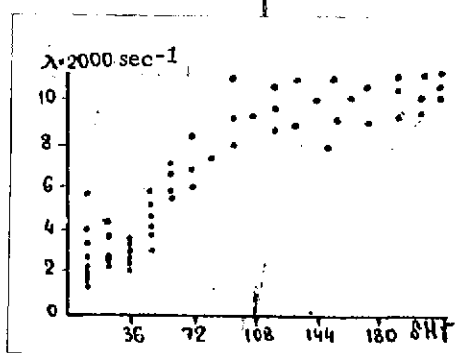

Fig. 1. Dependence of the damping of short-period oscillations observed on a bay on the magnitude of the bay [13].

The decrement of the hydromagnetic waves is related by the authors to the effective collision frequency [14]:

$$\lambda = \frac{\pi}{T^2 \sigma v_A^2}, \text{ where } \sigma = \frac{\omega_{pe}^2}{4\pi \nu_{eff}},$$

where T is the period of the short-period oscillations ($T \sim 40$-100 sec); v_A is the Alfven velocity; σ the conductivity of the turbulent plasma. However, the formula in [14] was derived for the damping of plane hydromagnetic waves due to pair collisions, while the short-period oscillations correspond to the guided hydromagnetic waves [21], for which the relationship should evidently be modified, retaining the proportionality $\lambda \sim \nu_{eff}$.

It should be noted that the appearance of VLF-radiation 1-2 minutes prior to a substorm indicates that the maximum generation of VLF takes place at the onset of the process.

From our viewpoint this is clearly related to the BUNEMAN stage, when the turbulence is more intense (i.e., the energy of the pulsations is greater than the thermal energy of the electrons). The level of the turbulence subsequently decreases, with heating of the electron gas, and non-isothermal conditions prevail.

Just as in [10], we shall assume that a constant electric field (or a field that is a weak function of time, E(t)) is "turned on" at some initial instant, somewhere in the magnetosphere (in the plasmosphere region). The source of this field may be the magnetosphere — for example, in the rapid genesis of unlike space charges on two parallel lines of force due to some external cause. The source of the field may also be ionospheric in nature (ionosphere dynamo [20, 19]. /6

We shall recapitulate briefly how the temporal evolution of the turbulent current takes place.

If the plasma is isothermal at the instant the electric field is "switched on" and $E > E_{D_2}$ (where E_{D_2} is the critical Dreiser field $E_{D_2} = e/\lambda_e^2$, $\lambda_e = v_{Te}/\omega_{pe}$), then, in the unbounded plasma, after a time of the order of a hundred plasma periods, BUNEMAN instability sets in, and the resulting turbulence does not permit free acceleration of the electrons with respect to the ions. Simultaneously with the process of turbulent inhibition, the electrons are rapidly heated (as compared with the ions). As a result, the plasma becomes non-isothermal ($T_e >> T_i$), and, after a time of the order of ($\sim \omega_{pi}$), ion-sound instability sets in and a quasi-stationary state is established with ion-sound turbulence. The quasi-stationary ion-sound turbulence evidently exists for a sufficiently long time.

Turbulent field-aligned currents in the Earth's magnetosphere occasion the appearance of geomagnetic disturbances (see [21]). We shall assume further that the time of existence of turbulence in the magnetosphere correlates with the duration of polar substorms — i.e., tens of minutes. /7

We wish here to consider the fact that in case of quasi-stationary ion-sound turbulence in the plasma a heating process accompanies the current at each point, since one of the basis characteristics of the quasi-stationary turbulence state is the anomalous dissipation of energy. The energy of the precipitating particles ε (t) grows with time from bay onset, i.e., from the instant E_0 is "switched on."

E(t), j(t), $\nu_{eff}(t)$ vary with the current at each point of the tube. In principle all of these quantities are observable, directly or indirectly.

In particular, the hydromagnetic waves passing through the plasma in this state evolve with time and decay.

In this paper we establish theoretically (semi-qualitatively) how the damping should depend on time. Finally, we compare the expected trend with that observed.

We anticipate that the damping effects (chiefly their temporal changes), in view of the anomalous plasma heating due to the anomalous current dissipation of a sub-storm, may serve as a plasma diagnostic method.

2. If the role of collisions between charged and neutral particles is negligible, the turbulent electro-conductivity of the plasma is completely determined by the spectrum of the ion-sound turbulence. This spectrum in turn depends on the field, and thus we obtain a self-consistent problem. /8

Some new results have been obtained recently on the problem of turbulent electrical conductivity. If we take into account the effects of correlated broadening $\Delta\omega$ of the wave spectrum, dissociation processes $S \rightarrow S' + S''$ become possible. Correlated broadening represents a loss of definition in the spectrum $\omega(\kappa)$; hence, with a sufficiently high level W_Z of turbulence energy, each $\vec{\kappa}$ no longer corresponds to a completely determinate $\omega(\vec{\kappa})$, but to some distribution function of finite width $\Delta\omega$ (and not to $\delta(\omega - \omega(\kappa))$.

From references [22, 23, 7], with the condition

$$E > E'_{xx} \tag{1}$$

it follows that the velocity-dependence of the turbulence energy is in the form

$$\frac{W^s}{nT} = \frac{1}{4}\sqrt{\frac{\pi}{8}}\frac{m_e}{m_i}\frac{v_0}{v_s} \simeq \frac{1}{100}\frac{v_0}{v_{Te}}. \tag{2}$$

The assumed volt-ampere characteristic [9] is here modified (Fig. 3). Namely, taking into account the dissociations $S \rightarrow S'_i + S''$, the flat section of the volt-ampere characteristic can be shortened and the relationship $j \sim E$ can even set in with the fields E'_{xx} (i.e., in the section DF). Let us examine this section of the volt-ampere characteristic in more detail.

Since $\nu_{eff} = \omega_{pe}W^S/nT$, taking (2) into account, we have /9

$$\nu_{eff} = \frac{\omega_{pe}}{100}\frac{v_0}{v_{Te}}. \tag{3}$$

Substituting γ_{eff} into Ohm's law,

$$j = ne v_0 = \sigma E, \tag{4}$$

where

$$\sigma = \frac{ne^2}{m\nu_{eff}} = \frac{\omega_{pe}^2}{4\pi\nu_{eff}}, \tag{5}$$

and as a result we find

$$v_0 = 10\sqrt{\frac{E e v_{ra}}{m\omega_{pe}}}. \tag{6}$$

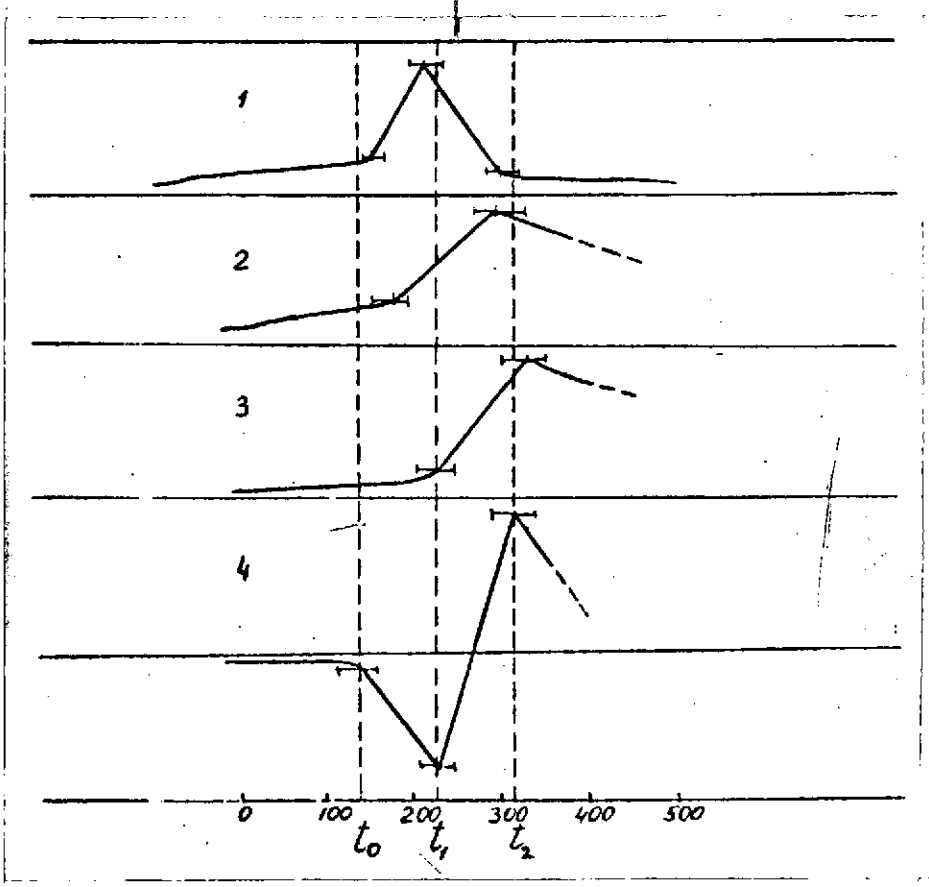

Fig. 2. Simultaneity of various phenomena connected with sub-storms [18]: 1) VLF-radiation. 2) Line λ5577 A intensity. 3) Absorption at cosmic radiation. 4) Z-component of geomagnetic field micropulsations.

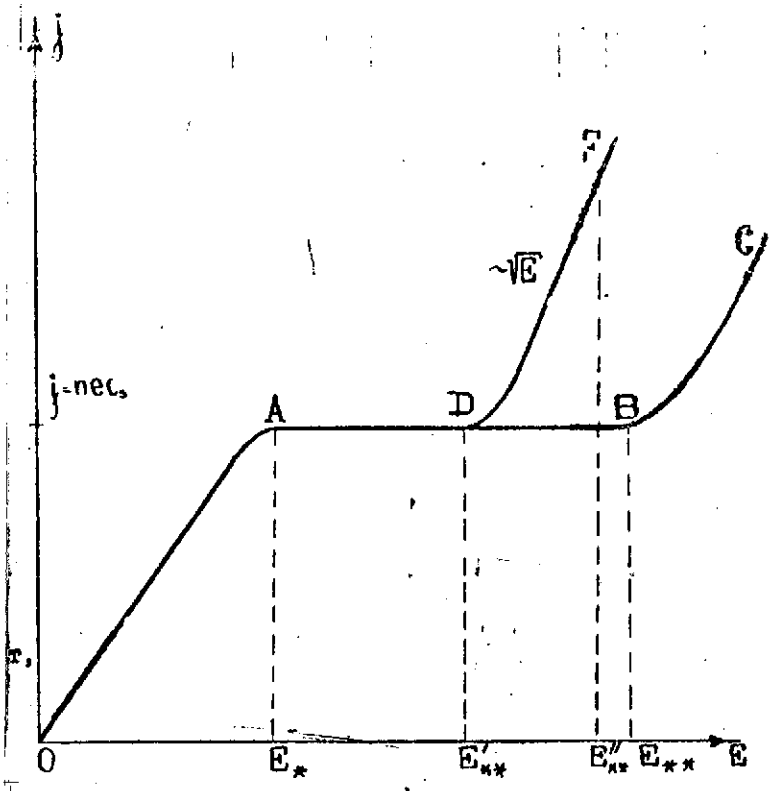

Fig. 3. Current in turbulent plasma as a function of the applied electromagnetic field [3-9].

The result (6) can also be expressed in terms of the Dreiser field $E_{De} = e/\lambda_e^2$, $\lambda_e = v_{Te}/\omega_{pe}$, and the number of particles in the Debye sphere $N_D = \frac{4}{3}\pi\lambda_e^2 n$

$$v_0 = 10 v_{Te} \sqrt{E/3N_D E_{De}} . \qquad (7)$$

The conductivity $\sigma^{(1)}$ corresponding to the section of the volt-ampere characteristic has the form

$$\sigma^{(1)} = \frac{\omega_{pe}^2}{4\pi\nu_{eff}} = \frac{\omega_{pe}}{4\pi}\frac{100 v_{Te}}{v_0} = \frac{10\omega_{pe}}{4\pi}\sqrt{\frac{3N_D E_{De}}{E}} = 10\sqrt{\frac{\omega_{pe} e n v_{Te}}{4\pi E}} . \qquad (8)$$

The theory [7] is found to be in accord with experiment [24], where the relationship $\sigma(\nu_0) \sim 1/\nu_0$ was observed, with $\nu_3 < \nu_0 < \nu_{Te}$.

We emphasize that the theory [7], deductions from which are cited here, is based on the assumption that the process $S \rightarrow S' + S''$ is dominant. This assumption corresponds to the deduction of very low angular diffusion θ (isotropic) as compared with the non-linear transfer of the waves along ω. These qualitative deductions are also substantiated experimentally. /10

Finally, we establish the limits of applicability of the state $j \sim \sqrt{E}$. The current in section AD is $j = nec_3$, and hence $\sigma^{(1)} = j/E = enc_3/E$. Equating $\sigma^{(0)} = \sigma^{(1)}$ at the point of joining D of the segments of the volt-ampere characteristic, we find E'_{xx} corresponding to this point:

$$E'_{xx} = \frac{3N_D E_{DR}}{100}\frac{m_e}{m_i} = \frac{4\pi e n v_{Te}}{100\omega_{pe}}\frac{m_e}{m_i} = \frac{\sqrt{4\pi}}{100}\frac{m_e}{m_i}\sqrt{nT_e}. \quad (9)$$

Formula (9) may also be expressed as

$$E'_{xx} = 0{,}73\cdot 10^{-8}\sqrt{nT_e(ev)}. \quad (9')$$

The upper bound of the regime [7] (point p on Fig. 3) is found as $E'_{xx} = 3N_D E_{DR}/100$. With $E > E''_{xx}$ we have strong turbulence.

Let us describe how we visualize the plasma heating process in an electric field and the corresponding development of a turbulent current. The results of the consideration will be applied to field-aligned currents in the magnetosphere in what follows. Let the electric field be "switched on" at $t = 0$ in an unbounded, non-isotropic plasma ($T_e >> T_i$). We shall assume that the BUNEMAN stage has already transpired. If $E > E'_{xx}$, the current corresponds to section DF of the volt-ampere characteristic.

Having assumed that $E = E_0 = \text{const}$ we write an equation that roughly describes the heating of plasma elements:

$$\frac{\partial}{\partial t}\frac{T_e}{2} = E_0 j = E_0 en\,10\sqrt{\frac{E_0 e v_{Te}}{m\omega_{pe}}} = 10nE_0^{\frac{3}{2}}T_e^{\frac{1}{4}}\sqrt{\frac{e^3}{m^{3/2}\omega_{pe}}} \quad (10)$$

Integrating (10), we have

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$$T_e^{3/4} = T_{e0}^{3/4} + 4t\sqrt{\frac{e^2 E_0^3}{m\sqrt{n}}} \tag{11}$$

or, for $T_e >> T_{eo}$

$$T_e \gg T_{e0}$$
$$T_e^{3/4} = 4t\sqrt{\frac{e^2 E_0^3}{m\sqrt{n}}}. \tag{12}$$

Here we consider the plasma to be homogeneous and E_0 to be independent of time.

After application of the field E_0, plasma heating takes place in accordance with (11) while the field E'_{xx}, whose growth with heating time is described by (9), is not equal to E_0. It would be expected that subsequent to this heating would proceed in accordance with the quasi-linear theory [4, 5].

Substituting $E_0 = E'_{xx} = \frac{\sqrt{4\pi}}{100}\frac{m_e}{m_i}\sqrt{nT_e}$ into (12), we find the duration of heating described by (12):

$$t_0 = \frac{250}{4\sqrt{4\pi}}\left(\frac{m_i}{m_e}\right)^{3/2}\omega_{pe}^{-1} \approx \frac{180}{\sqrt{n}} \tag{13}$$

With $t > t_0$, quasi-linear heating [8] is described by the equation

$$\frac{\partial nT_e}{\partial t} = E_0 ne\sqrt{\frac{T_e}{m_i}} \quad \text{with} \quad E_0 < E'_{xx}, \tag{14}$$

from which

$$\sqrt{T_e} = \sqrt{T_{e0}} + \frac{eE_0}{2\sqrt{m_i}}t. \tag{15}$$

Under actual conditions, for example in the magnetosphere, it is difficult to anticipate whether the field E_0 will remain constant long enough — specifically, conforming to the time of development of sub-storms. It is therefore useful to evaluate this same

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heating process for some simple model of a field that falls off in time.

For example, let $E = E_0 / 1 + \frac{t}{\tau}$.

Then the equation describing the heating of electrons in section DP of the volt-ampere characteristic has the form

$$T_e^{\frac{3}{4}} = T_{e0}^{\frac{3}{4}} + 15\tau \sqrt{\frac{e^3 E_0^3}{m_e^{3/2} \omega_{pe}}} \left(1 - \frac{1}{\sqrt{1 + \frac{t}{\tau}}}\right). \tag{16}$$

The duration of the stage of heating described by (16) will be t_0, which is estimated similarly (13)

$$t_0 = \frac{\tau}{9}\left(\frac{2\left(2 + \frac{a}{\tau}\right)}{\sqrt{4 + \frac{a}{\tau}} - 1} + \frac{\left(2 + \frac{a}{\tau}\right)^2}{\left(\sqrt{4 + \frac{a}{\tau}} - 1\right)^2} - 8\right) \tag{17}$$

where

$$a = \frac{225\, m_i^{3/2} \omega_{pe}^2}{\pi^{3/2} e^3 n^{3/2}} \approx \frac{27 \cdot 10^2}{\sqrt{n}}.$$

The subsequent course of the heating takes place in the quasi-linear regime described by the equation

$$\frac{\partial n T_e}{\partial t} = \frac{E_0}{1 + \frac{t}{\tau}} n \sqrt{\frac{T_e}{m_i}}, \tag{18}$$

from which

$$\sqrt{T_e} = \frac{e E_0 \tau}{2\sqrt{m_i}} \ln\left(1 + \frac{t}{\tau}\right) + \sqrt{T_{0e}}. \tag{19}$$

We emphasize that in both cases (constant- and decreasing-field) t_0 (illegible in text) does not depend on the initial value of the field.

3. It is reasonable to assume that the processes described above take place in the / 13
Earth's magnetosphere. According to the available data the electric fields along the geomagnetic field lines are of the order of 10^6–10^8 v/cm.

The lifetime of the currents created by these fields is reasonably identified with the time of growth of polar sub-storms — i.e., from 30 minutes to two hours. In (9'), for example, setting $E'_{xx} = 0.73 \cdot 10^{-8} \sqrt{n T_e}$, $n = 10^4$ cm^{-3} and Te = 10 Kev, we find $E'_{xx} = 0.7 \times 10^{-4}$ v/cm, and with $n = 10$ cm^{-3} and Te = 0.1 ev, $E'_{xx} = 0.7 \times 10^{-8}$ v/cm. For $n = 10^2$ cm^{-3} and Te = 10 ev, we have $E'_{xx} = 0.7 \times 10^{-6}$ v/cm.

From these estimates pertaining to the magnetosphere we see that in the magnetosphere we can expect an initial heating stage governed by (11) or (16) over a time t_0. Then heating will proceed in accordance with (15) or (19), for constant or declining fields, respectively. We shall now estimate the time t_0. For example, with $E = E_0 = 10^6$ v/cm and $n = 10^4$ cm^{-3}, $t_0 = 1.8$ sec. After this the electron gas heats up to Te = 3–4 ev in the unbounded plasma (with an initial temperature $T_e \sim 1$ ev). If we take $n = 10^2$ cm^{-3} we obtain, respectively, $t_0 = 18$ sec and heating to $T_e = 100$ ev. Similar estimates for a decreasing field, with $E = E_0/(1 + t/\tau)$, where $\tau = 40$ sec, yield an insignificant increase in t_0 and T_e.

Subsequent heating in accordance with (15), with $E_0 = $ const., for example, yield estimates of 1 keV with $E_0 = 10^6$ v/cm after t = 60 sec.

With a decreasing $E(t) = E_0/(1 + t/\tau)$, $\tau = 40$ sec, the heating time to 10 keV is 6000 sec. / 14

The latter estimate more closely corresponds to actual measurements, as does also, generally speaking, the declining field method.

We note here that the growth with time of the energy of the precipitating particles of auroral sub-storms has been given detailed consideration in reference [25].

It should be emphasized that we have thus far made estimates for an unbounded plasma. But if we take a line of force of length l of the order of 5×10^9 cm, then, with an electron velocity $v \sim c_e \simeq \sqrt{\frac{T_e}{m_e}}$, we find that the total time of drift of the electrons along the lines of force is no more than $t_1 \sim l/c_e \sim 5000$ sec for $T_e = 1$ ev (illegible in text) and t_1 is no greater than 50 sec for $T_e = 10$ keV.

Considering that the theory developed for the unbounded plasma is, strictly speaking, applied for times less than the time of drift along a tube of force, under

magnetosphere conditions the description of the heating at sufficiently high temperatures can be considered to be only qualitatively correct.

4. The temporal trend of the turbulent heating, as described in the last section, can be used to interpret certain geophysical observations. As we know, the collective collision frequency in a plasma is estimated as $\nu_{eff} = \omega_{pe} W^3/nT$. Here, after a time less than t_0, according to (2), (6), and (11)

$$\nu_{eff} = \frac{\omega_{pe}}{10}\sqrt{\frac{eE_0}{m_e\omega_{pe}^2 r_{Te}}} \sim T_e^{-1/4} \sim t^{-1/3}$$

for $E = E_0 = \text{const}$.

For a time $t > t_0$ the time dependence of ν_{eff}, for constant E_0 and decreasing $E = E_0/(1 + t/\tau)$ is expressed by

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$$\text{for } E = \text{const}: \quad \nu_{eff} = \omega_{pe}\frac{W^3}{nT} = \omega_{pe}\frac{E_0^{1/2}}{(8\pi n T_e)^{1/4}} = \sqrt{\frac{\omega_{pe}}{t}}\left(\frac{2m_i}{m_e}\right)^{1/4} \tag{20}$$

$$\text{for } E = E(t): \quad \nu_{eff} = \frac{\omega_{pe} E_0^{1/2}}{\left(1+\frac{t}{\tau}\right)^{1/2}(8\pi n)^{1/4}\left(\frac{eE_0\tau}{2\sqrt{m_i}}\ln\left(1+\frac{t}{\tau}\right)\right)^{1/2}}. \tag{21}$$

From the latter formula, in particular, we can draw the qualitative conclusion that the collective collision frequency falls off by about one order after a time of the order of the duration of sub-storms.

Let us proceed to the experimental confirmation of this conclusion, taking ν_{eff} to be proportional to the damping of the short-period oscillations (Pe-4, Pi-2) observed on the background of a bay.

In this paper we have considered the damping factor of the short-period oscillations observed against the background of a bay. Inasmuch as each bay is a particularly unique event, we compared the damping factor for the short-period oscillations observed against the background of the same bay.

From March 1967-March 1969, 13 such cases were selected in which short-period oscillations were observed against the background of each bay and for which the decrement could be computed for at least two wave-trains.

Magnetograms from the P-Tungusk station were processed with a scan rate of 90 mm/hr and a sensitivity of 0.4-0.5 γ/mm for the horizontal D- and H- components.

Only those bays were selected whose fields had been quiet for at least 2 hours prior to onset.

The decrement was computed for those short-period oscillation wave-trains having 3-4 oscillations and which were more or less normal in nature, so that within the error limits the period remained constant throughout the wave-train. The error in estimating the decrement was ~ 20% - 25%. / 16

The decrement was defined as $1/t_e = \lambda$, where t_e is the time taken for the pulsation amplitude to decrease by a factor of e.

It should be noted here that points corresponding to a decrement faster than 2-3 periods were not considered, since they as a rule relate to short wave-trains and the constancy of the period is not maintained to within the error limits. It was noted that the decrements of the short-period oscillations observed on the same bay were usually larger for the first wave-train than for the second.

Figure 4 shows the magnetogram reductions: t/t_δ is plotted on the abscissa, where t is the time from onset of the bay when the short-period oscillations were observed and t_δ is the duration of the bay.

The relative decrement $\lambda/\omega = T/t_e$ is plotted on the ordinate. Of the 13 cases considered, in 12 the decrement decreased with increasing relative time, and the straight lines in Fig. 4 have negative slopes.

If we take the decrement as being proportional to the effective collision frequency of the electrons in the turbulent pulsations, we obtain a result that is in accord with the theoretical representation of the development of ion-sound turbulence.

In concluding, the authors thank L. L. Vanʲyan for assistance with this problem and for many useful discussions, and V. N. Tsitovich and V. F. Shelʲting for their interest in the work and for reviewing the results. / 17

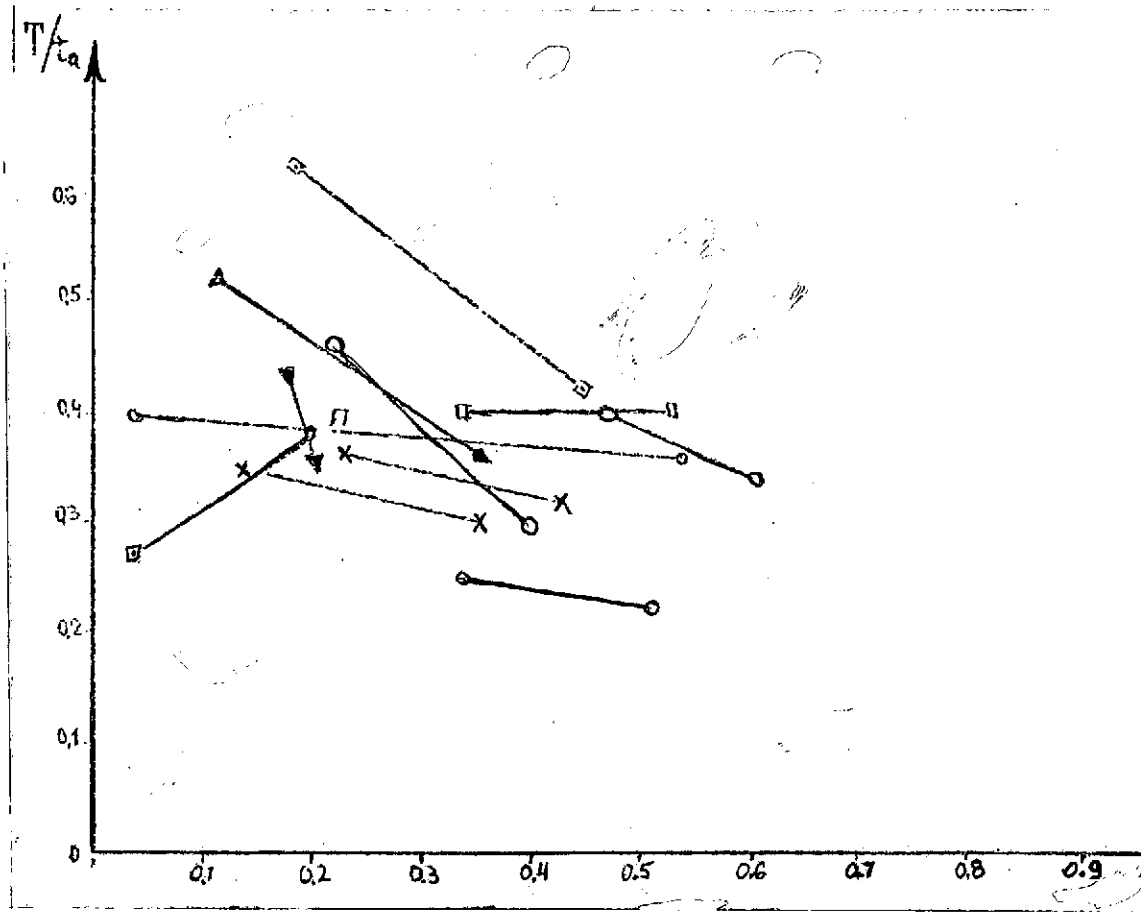

Fig. 4. Bay developments.

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